of energies extending between well-defined limits that can be readily calculated from the collision kinematics. These low-energy neutrons destroy the purity of the neutrons from the T(d,n)He[4] reaction. At some high energy (certainly above 8.9 Mev) a similar contamination of the D(d,n)He[3] reaction is probable. Thus at high energies it will be necessary to use an associated-particle coincidence technique[10] in order to perform neutron experiments which are sensitive to low-energy neutrons. Unfortunately, such experiments will be complicated and the useful neutron yield will be low when associated-particle coincidence counting is required.

† Work performed under the auspices of the U. S. Atomic Energy Commission.

1 The proton-recoil neutron spectrometer used in this experiment was a modification of the coincidence-telescope spectrometer described by F. L. Ribe and J. D. Seagrave, Phys. Rev. **94**, 934 (1954).

2 A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).

3 In Table I and in the text where complete reactions are cited, the bombarding particle is that symbol which occurs first inside the parentheses. As an abbreviation in the text and figures the *breakup* reactions are indicated by two symbols, the first being the incident particle and the second the target nucleus.

4 That the extraneous neutrons have low energy has been directly measured in the two cases *pd* and *dt* (miscellaneous unpublished work by the authors). That neutrons from *d*He[3] and *d*He[4] must have low energy is assumed from their appearance only above a threshold, an argument which also applies to the *pd* and *dt* cases.

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Experimental Checks of the Statistical Theory of Nuclear Reactions*

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THE basic features of the statistical model,[1,2] briefly stated, are (1) validity of the compound nucleus assumptions that (a) a nuclear reaction involves the immediate formation of a compound state with rapid statistical sharing of energy among all the nucleons and (b) disintegration of the compound state is independent of its mode of formation; (2) reduced widths to various levels of the residual nucleus are all the same (this gives rise to a Maxwellian-type energy distribution for emitted particles); (3) interference terms average out; (4) level density of the residual nucleus is proportional to $2j+1$, where j is the level spin.

It has long been recognized that the spatial and spectral distributions of the products of inelastic interactions provide a sensitive test of the validity of the compound nucleus concept in general and the statistical model in particular. Furthermore, advantages of avoiding the complications of Coulomb effects argue strongly for experiments in which both the incident and emitted particles are uncharged.

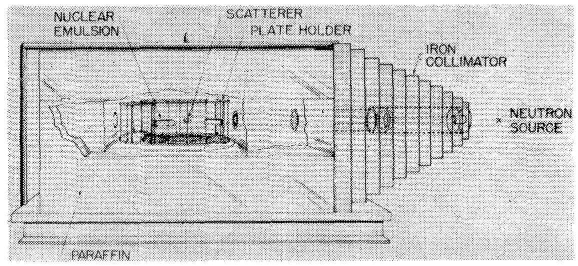

FIG. 1. Experimental arrangement for measuring the spectral and spatial distributions of neutrons from neutron induced reactions. The collimator defines a beam of neutrons only slightly larger than the scatterer. The nuclear plates are arranged with their axes all passing through the center of the scatterer and making angles of 20°–150° with respect to the incident beam direction.

The energy spectra of most of the neutrons resulting from nonelastic interactions of 14-Mev neutrons with medium weight and heavy nuclei[3] are in accord with assumptions (1) and (2). However, since these experiments are integral experiments they provide little information with regard to assumptions (3) and (4). To test these assumptions, one can investigate the angular distribution of the nonelastic neutrons.

An experiment was therefore designed to measure the distribution in energy and angle of the neutrons resulting from the incidence of 14-Mev neutrons on various elements. The experimental arrangement is indicated in Fig. 1. Thus far, data have been obtained only on bismuth and even these are preliminary.

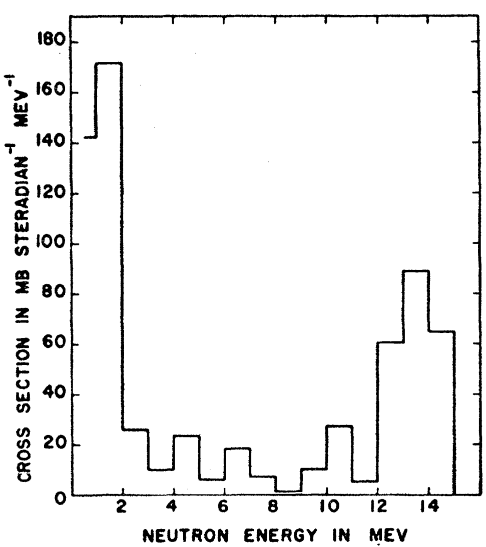

FIG. 2. Cross section for the emission of neutrons *vs* neutron energy at 30°.

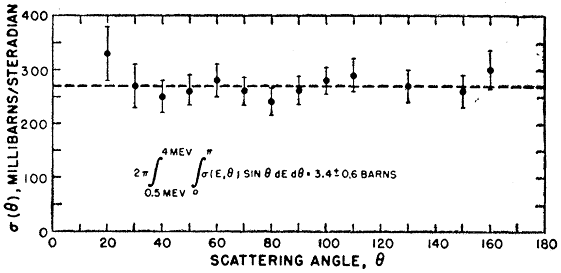

FIG. 3. Angular distribution of neutrons of energy 0.5–4.0 Mev.

Figure 2 shows the kind of information one obtains at each detector position. The high-energy group is due to elastic scattering. Figure 3 shows the angular distribution of the low-energy (0.5–4.0-Mev) neutrons. It is seen that there is not only symmetry about 90° [in accord with feature (3)], but also isotropy [in agreement with feature (4)].[4]

In contrast, the angular distribution of the high-energy (4.0–12.0-Mev) nonelastic neutrons (Fig. 4) is strongly peaked in the forward direction, indicative of nucleon-nucleon interactions. An attractive way of looking at this phenomenon is to invoke the model of Thomas[5] which divides the nucleus into two regions, an inner strong-interaction region and an outer region where the interactions are relatively weak. It is presumably this outer region which is responsible for the noncompound nucleus processes as indicated by the data. The important point, however, is that only ~0.2 barn out of a total inelastic collision cross section of 2.5 barns[6] is associated with neutrons which have spectral and spatial distributions at variance with the above listed assumptions. (Part of the 4–12-Mev neutrons have an isotropic distribution and may represent the tail of the Maxwellian which described the low-energy neutrons.)

In evaluating the validity of the statistical model, one should bear in mind the following additional points: (1) It would appear that energy distributions of low-energy inelastic neutrons and protons may not lead to a reliable estimate of level densities or nuclear "temperatures" because, when energetically possible, the decay of the compound nucleus presumably takes place by the emission of more than one particle. Calculations[7] show that $(n,2n)$ reactions have a marked effect on the apparent nuclear "temperatures" deduced from neutron energy distributions. (2) In experiments involving charged particles,[8] it would appear that the forward-peaked angular distributions which are observed probably account for only a small fraction of the total inelastic cross section. (3) Emission of low-energy protons from heavy nuclei is not necessarily inconsistent with the compound nucleus concept. Such protons may arise when an $(X,2n)$ reaction is energetically forbidden, while an (X,np) reaction is not.

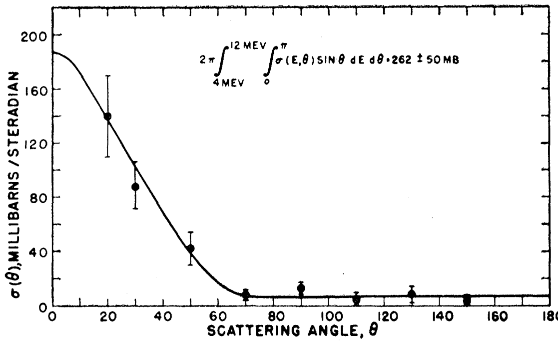

FIG. 4. Angular distribution of neutrons of energy 4.0–12.0 Mev.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

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Shell Effect on Photonuclear Reactions*

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A PREVIOUS analysis of some experimental data on photonuclear reactions led the authors[1] to point out that the mean-square displacement of nucleons in the nuclear ground state presents evidence in favor of an alpha-particle structure of nuclei. Although the theoretical basis for this conclusion is not free of criticism—since correlations were neglected in the formula for the harmonic mean energy[2] of photon absorption, which we used—this evidence might be investigated experimentally in a more direct way at higher energies.

On the other hand, the shell structure of nuclei has been revealed, in the energy region of the photonuclear effect, by Nathans and Halpern.[3] Features of different nuclear models are expected to be presented by nuclear

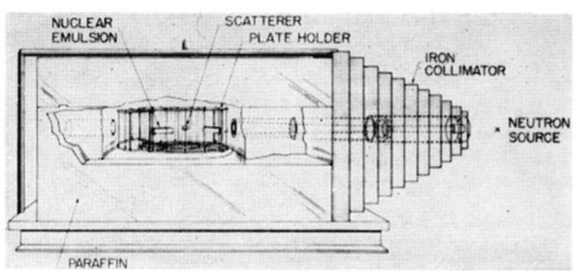

FIG. 1. Experimental arrangement for measuring the spectral and spatial distributions of neutrons from neutron induced reactions. The collimator defines a beam of neutrons only slightly larger than the scatterer. The nuclear plates are arranged with their axes all passing through the center of the scatterer and making angles of $20° - 150°$ with respect to the incident beam direction.